Horn 1 Stripline Analysis for 1 MW Operation

Ang Lee

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Introduction

The initial analysis[1] of Horn 1 stripline done by Z. Tang indicates the maximum temperature of the aluminum plate can go as high as 139 C around the flag area for 1 MW operation. With the most recent experiment work done by Cory Crowley and Georgi Lolov for the convective film coefficient, we have updated the analysis work accordingly. It is an extension of earlier study.

FEA model

1) The geometry and original workbench file are provided by Zhijing Tang and the latest film coefficient is provided by Cory Crowley and Georgi Lolov.
2) The current pulse is 200 KA peak value (half sine) with a duration of 2.3 ms for every 1.2 sec.
3) The beam heating data is provided by MARS simulation for 1 MW.
4) The material property is the same as reference 1. The temperature dependency of resistivity is considered.

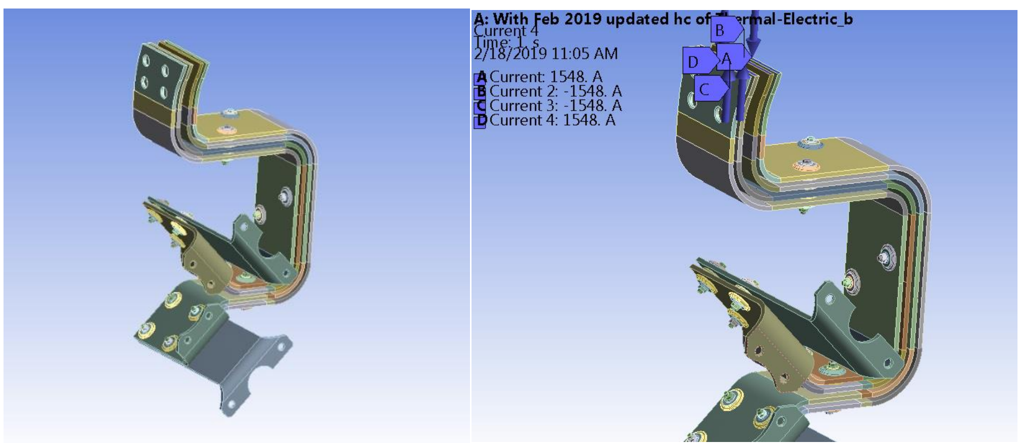


Fig 1 FEA model

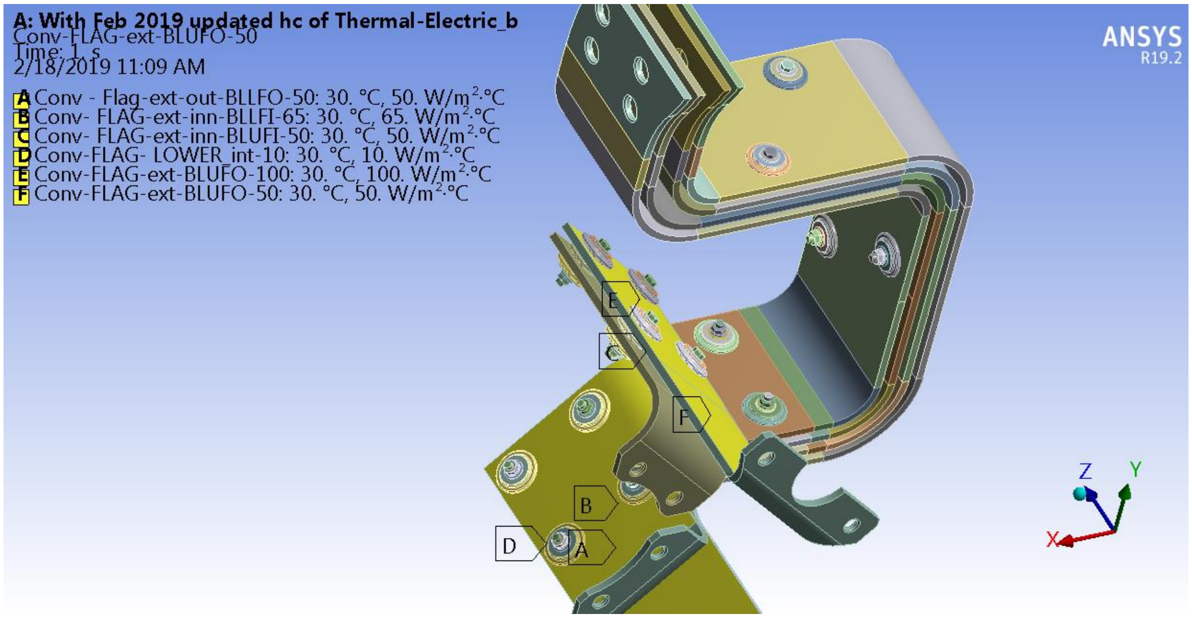


Fig 2a the convective film coefficient measured by Cory and George around flag area (see more detail in Appendix A)

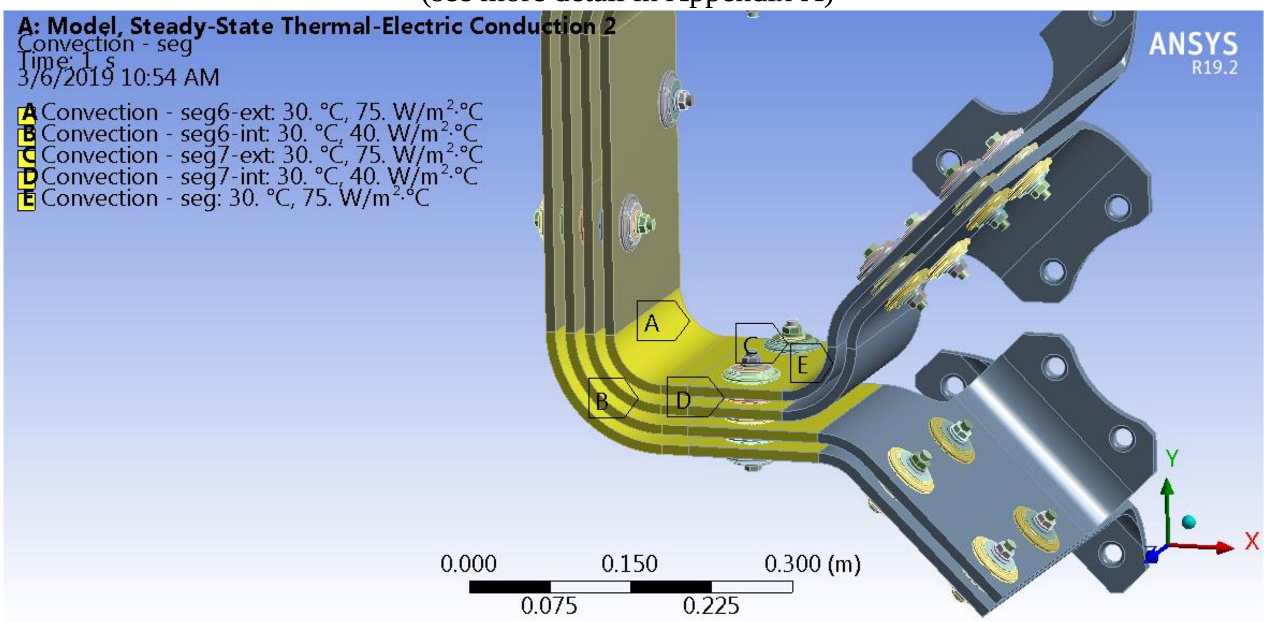


Fig 2b the convective film coefficient measured by Cory and George around other area

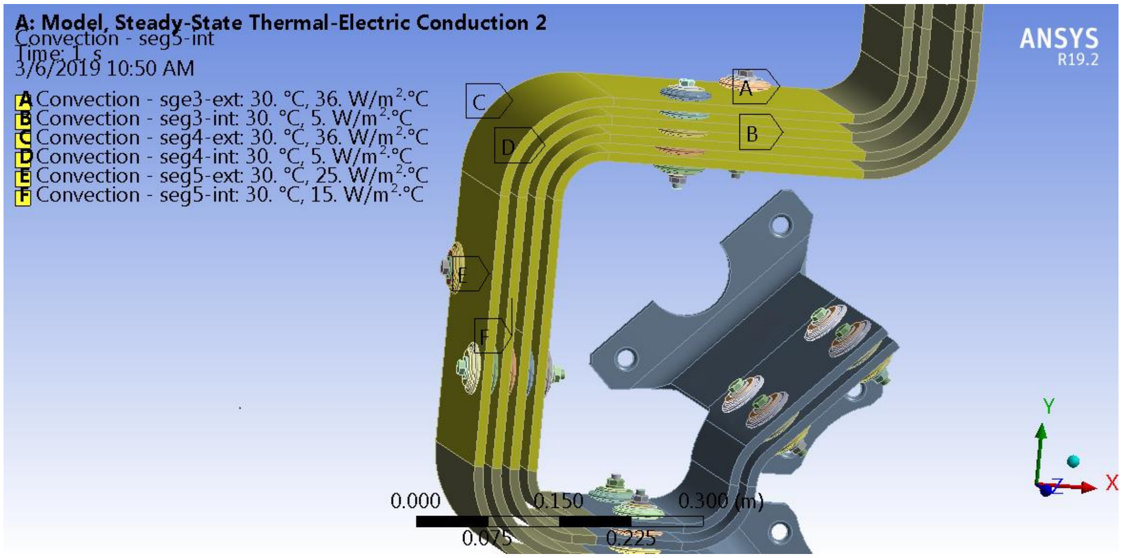


Fig 2c the convective film coefficient around upper area

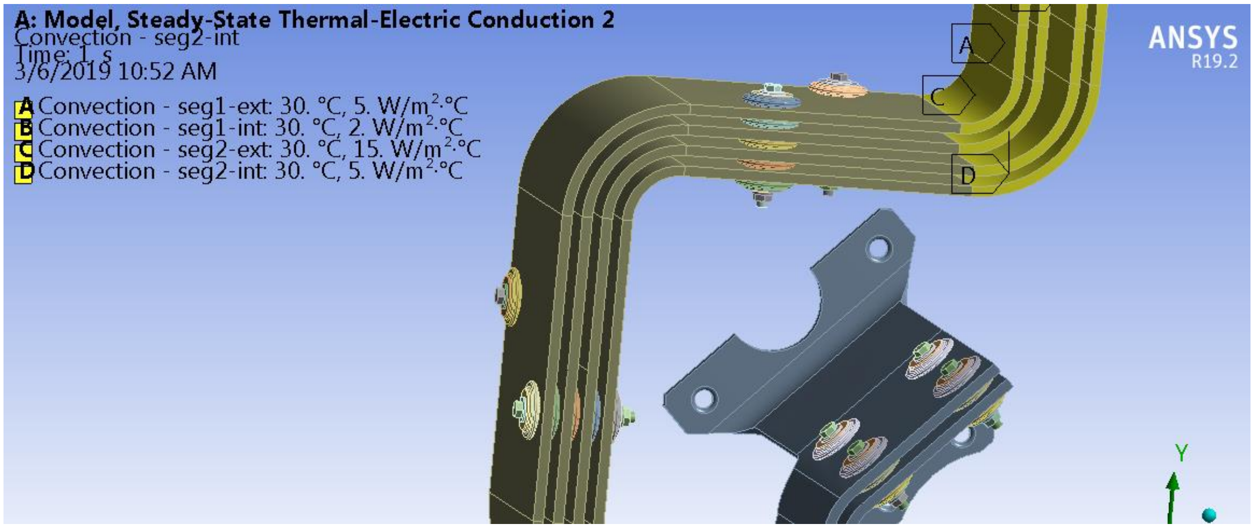


Fig 2d the convective film coefficient around upper area

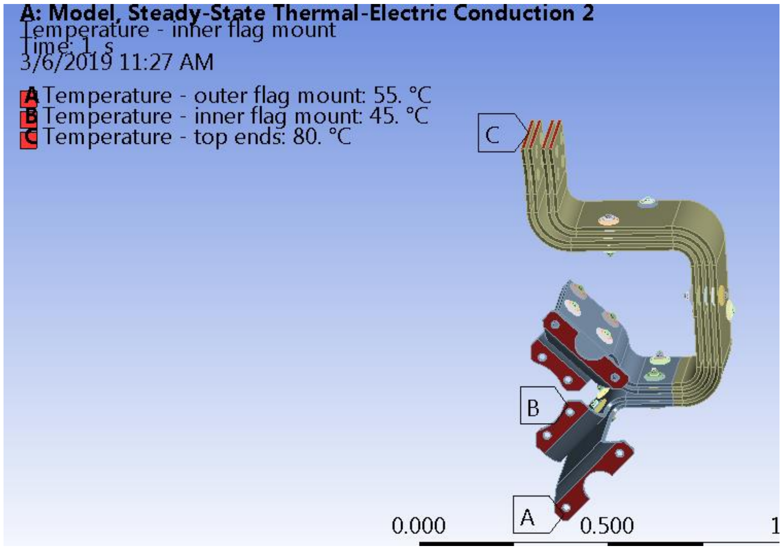


Fig 2e the temperature constraint for the thermal model

Result and Discussion

Thermal Result

1) The steady state indicates the maximum temperature of the stripline is about 100.25 C (both beam and joule heating) as shown in Fig 3 It is located at the upper section of the inner layers.
2) The majority heating source is from the beam energy as shown in Fig 4.
3) The FEA model uses multi-physics element to calculate the joule heating internally as shown in Fig 5 and 6. The current density is higher at the corner area, so does the joule heating.
4) The transient effect is very small as shown in Fig 7. It is consistent with the earlier finding[1].

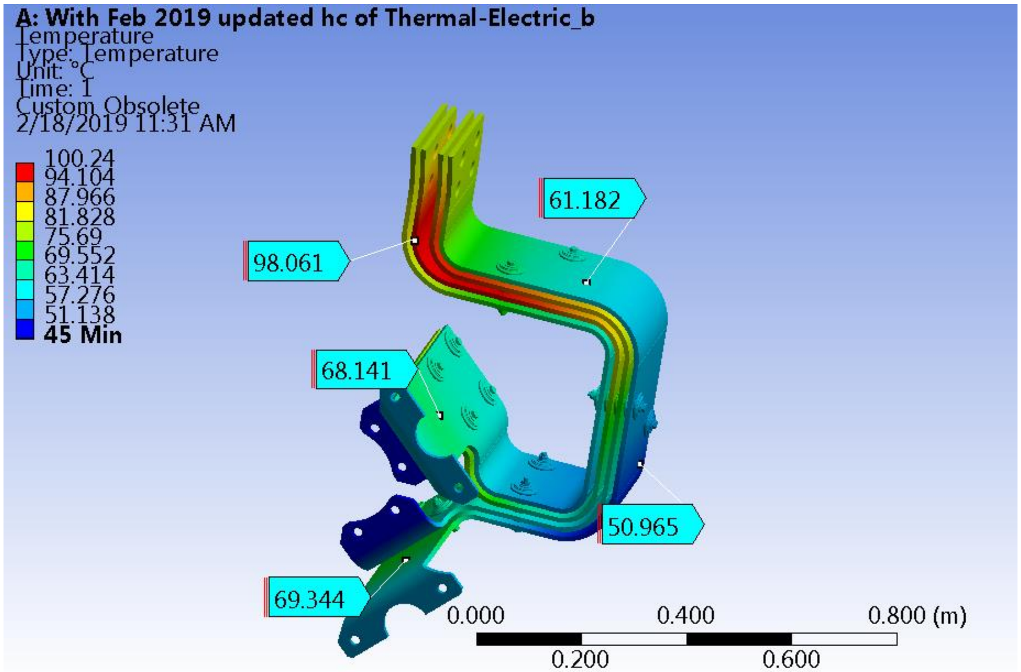


Fig 3 the steady state temperature of the stripline
(including both joule and beam heating)

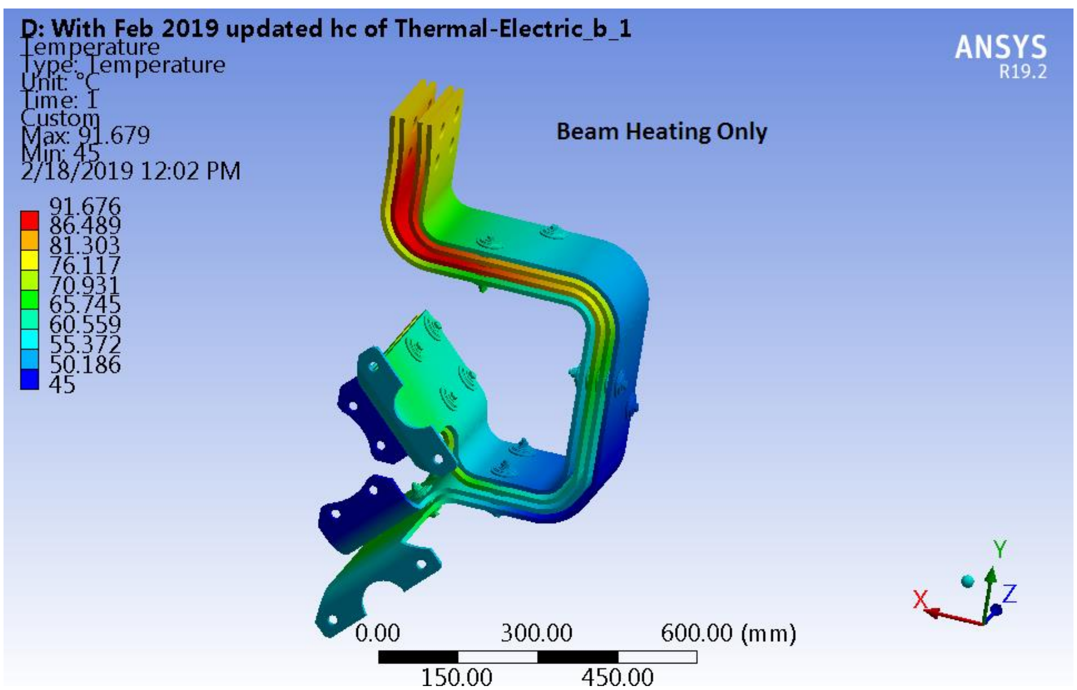


Fig 4 the temperature due to the beam heating only

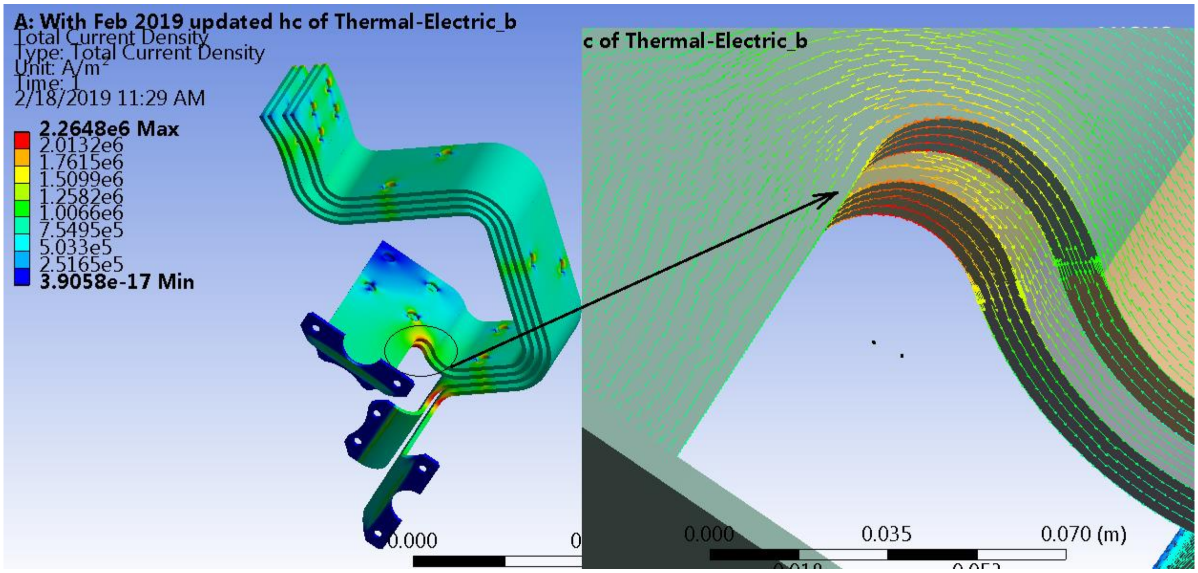


Fig 5 the current density, the corner region is higher

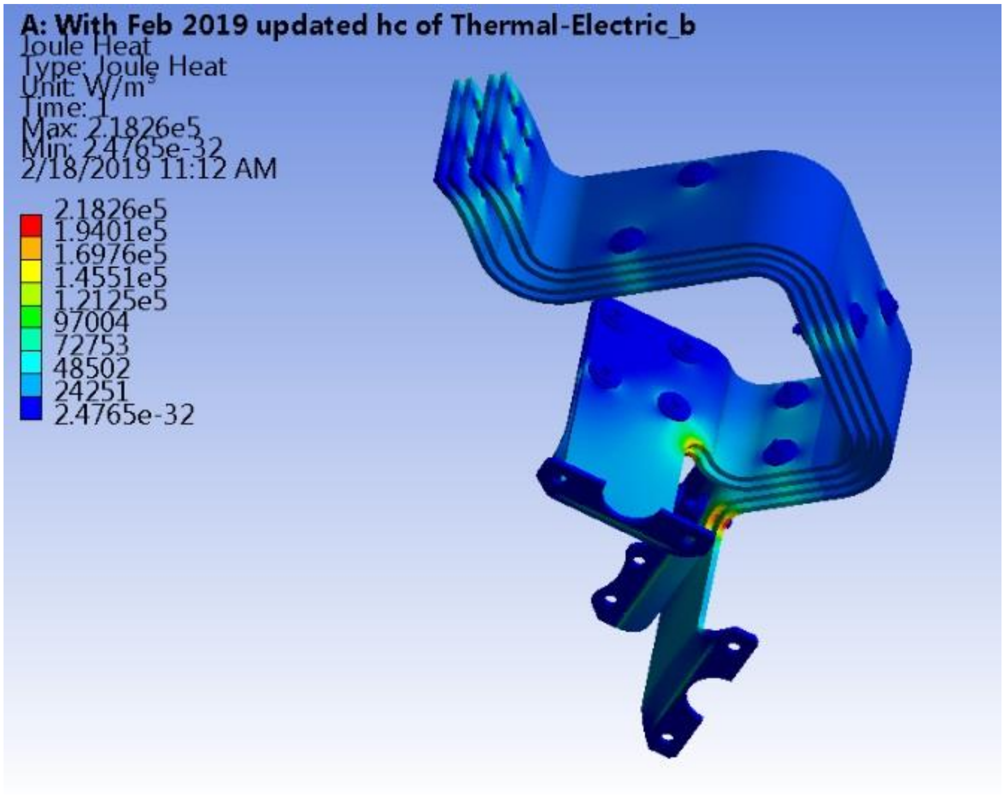


Fig 6 the joule heating plot

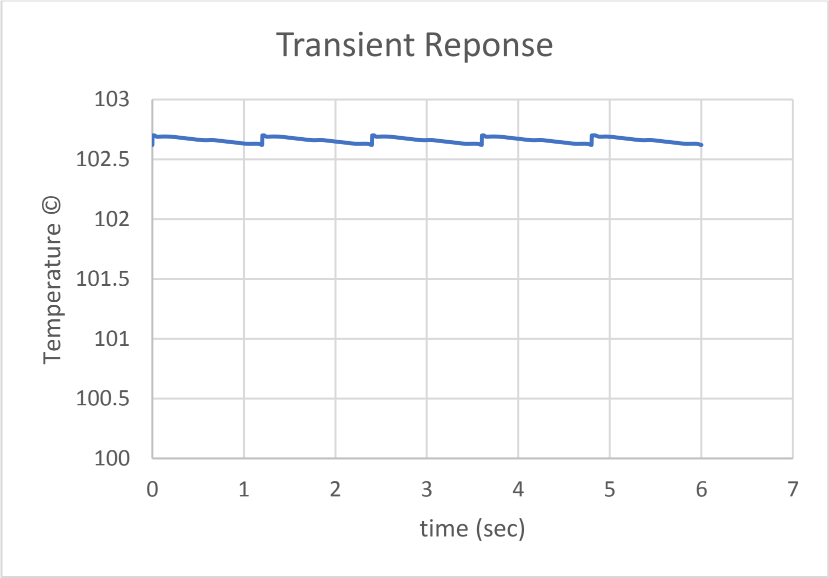


Fig 7 the transient response

The Structural Result

The thermal response indicates that the transient effect is very small. Therefore, we'll use steady state to calculate the thermal stress as Smin, and thermal+ magnetic load as Smax. The Goodman equation is used to evaluate the fatigue. The structure model consists of following:

1) A bolt preload up to 6800 lbf (30248 N).
2) Structure gravity
3) Thermal stress (steady state temperature, Tref is 30 C).
4) Thermal + Magnetic load based on ref (1) work.
5) The contact between the ceramic washer and stripline is treated as "frictional contact", which yields a more realistic result than "bonded" case. But it requires more computational effort.
6) A sub model is used to cross check the stress result around the bolt hole area to insure the quality of the calculation.
7) A Goodman equation is used to evaluate the fatigue.

Table 1 Material Strength taken from reference (1)

Alloy/Temper	Ultimate stress (MPa)	Yield stress (MPa)	No of cycles	Fatigue Stress (MPa)
6101-T6	200	172	10^8	60
6013-T6	311	286	10^8	124

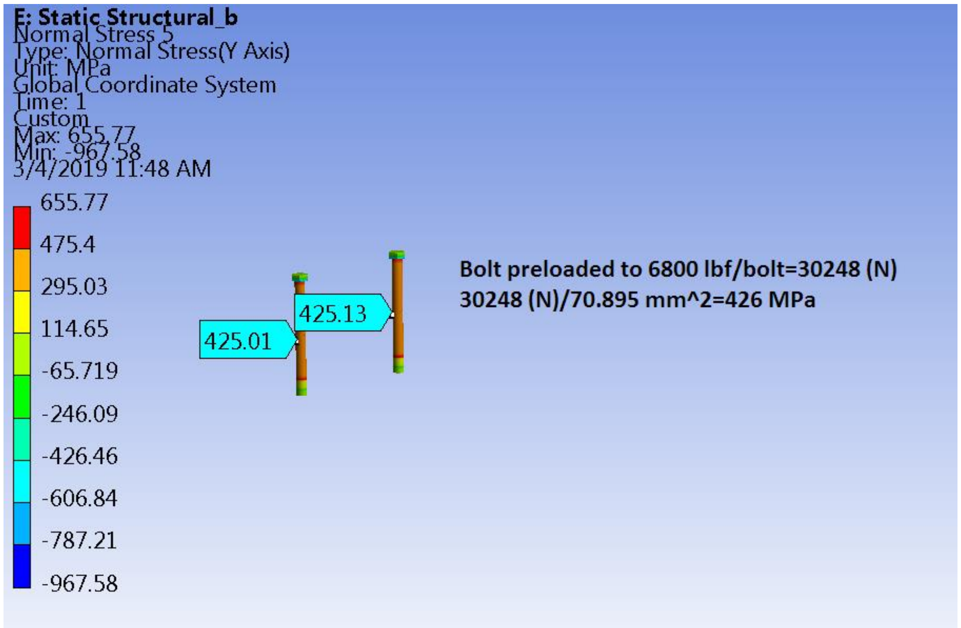


Fig 8 the bolt preload up to 6800 lbf (30248 N)/bolt

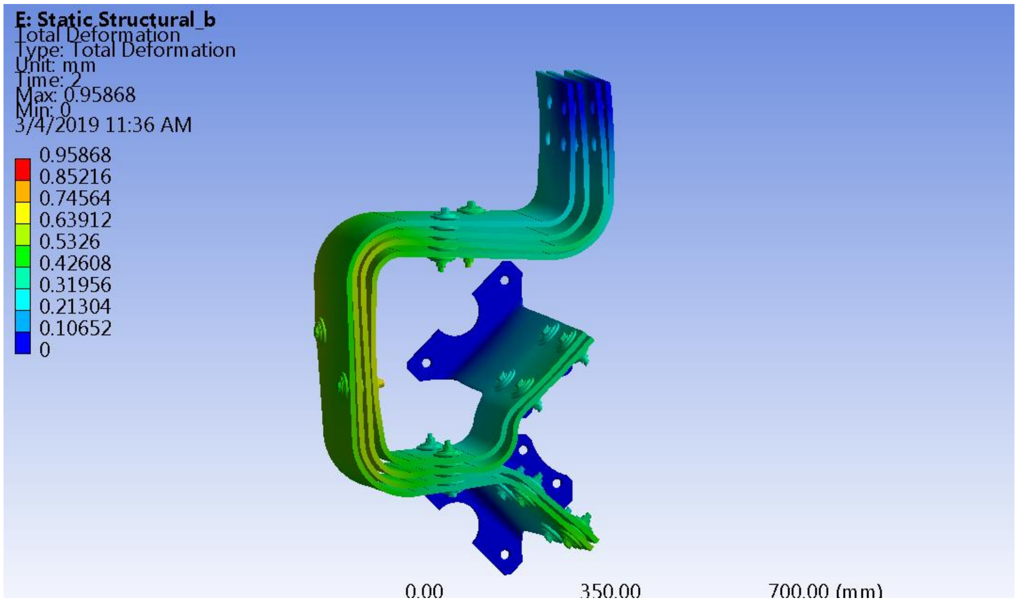


Fig 9 Stripline Deformation (mm) due to the thermal load

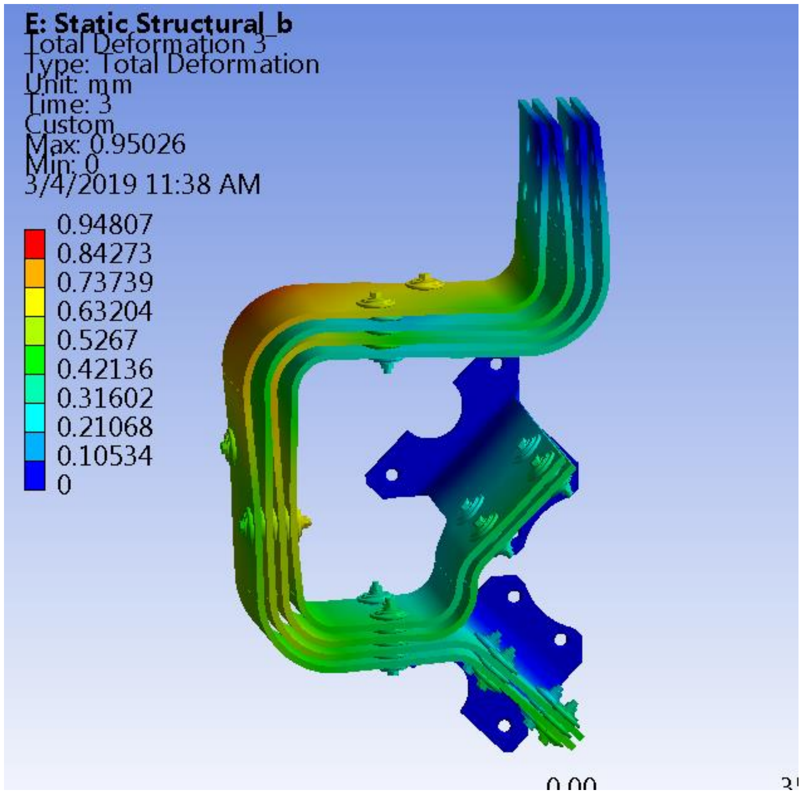


Fig 10 the stripline deformation (mm) due to the thermal + magnetic load

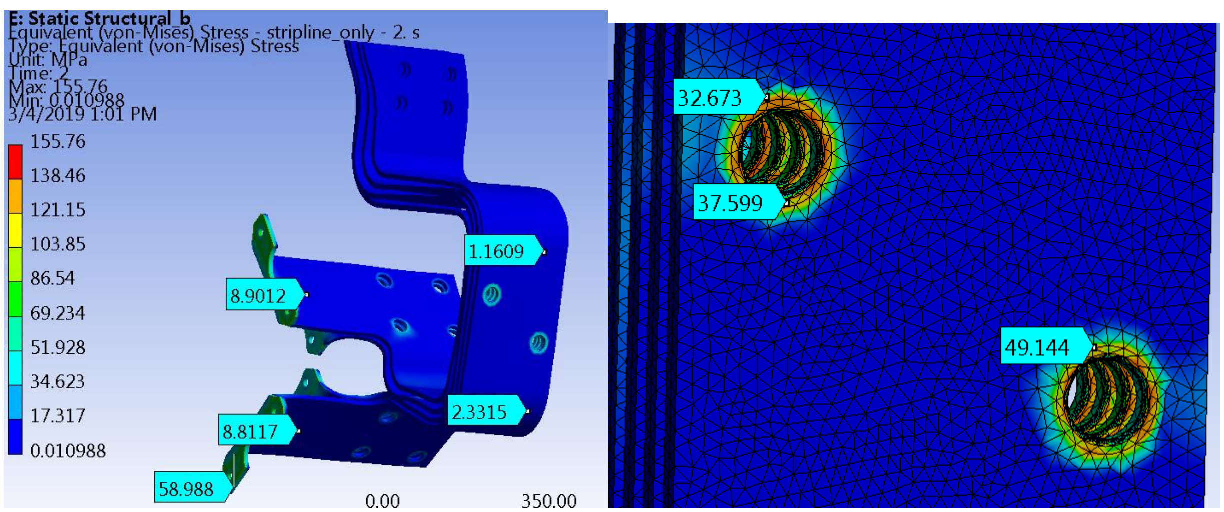


Fig 11 the thermal Stress (50 MPa=7.25 ksi).

The stress is very mild almost everywhere, except at the connection due to the constrain (see Fig 12) and bolt area due to the preload. The yield stress of 6101-T6 is 172 MPa and 286 MPa for 6013-T6

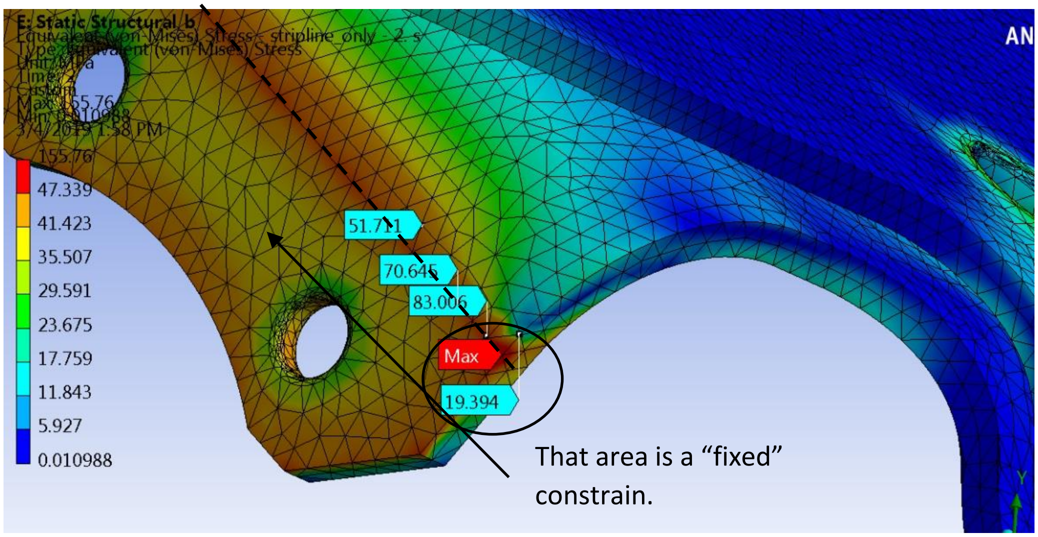


Fig 12a the stress around connection area (with the horn) where the surface is a fixed BC

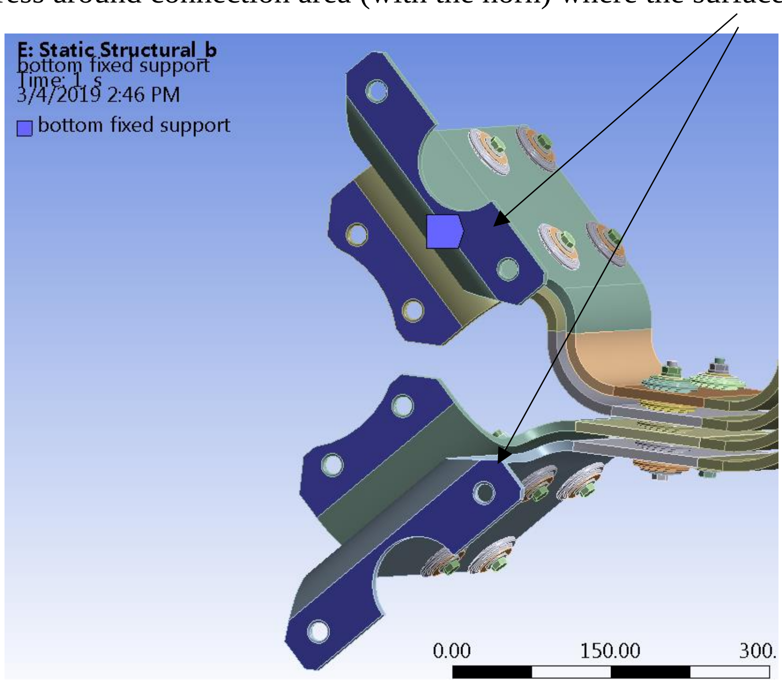


Fig 12b the shaded area (blue) is a fixed boundary condition (UX, UY and UZ=0)

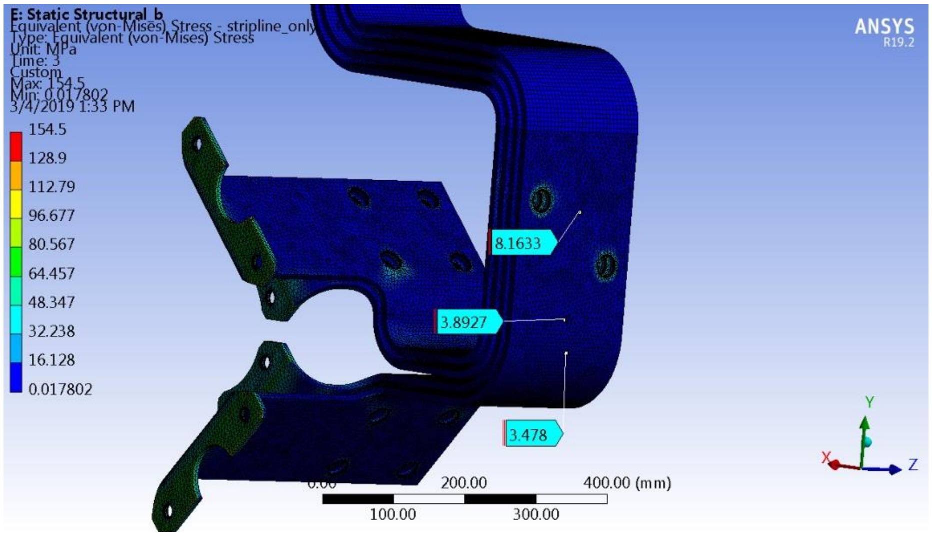


Fig 13 the stripline stress due to magnetic + thermal load.

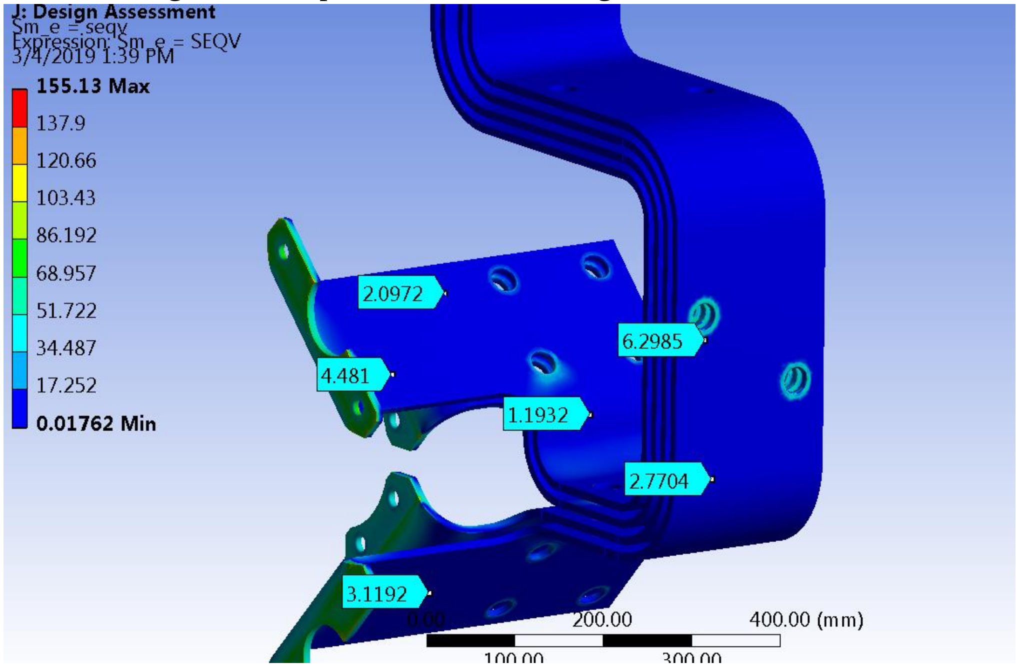


Fig 14 the mean stress Sm (MPa).
(The yield stress of 6101-T6 is 172 MPa and 286 MPa for 6013-T6)

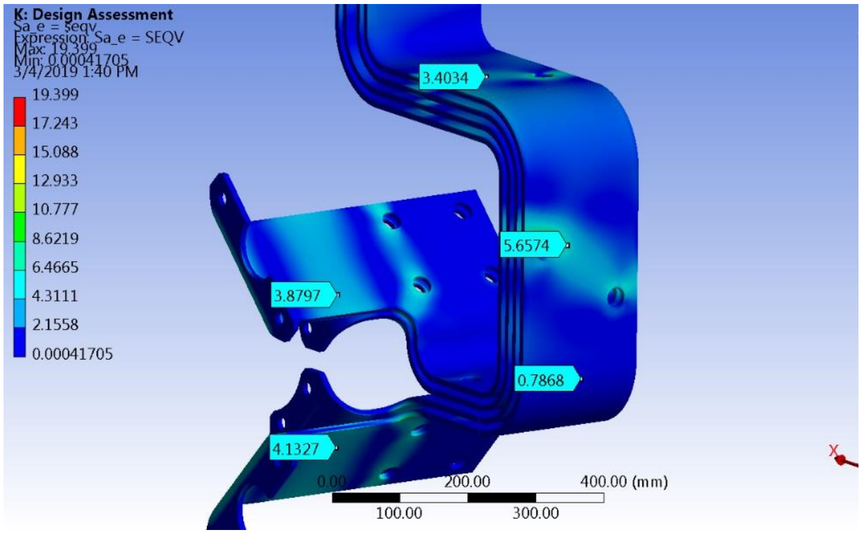


Fig 15 the Alternating stress (MPa).

The fatigue stress of 100e6 cycles for Al 6101-T6 is 60 MPa and 124 MPa for 6013-T6 respectively.

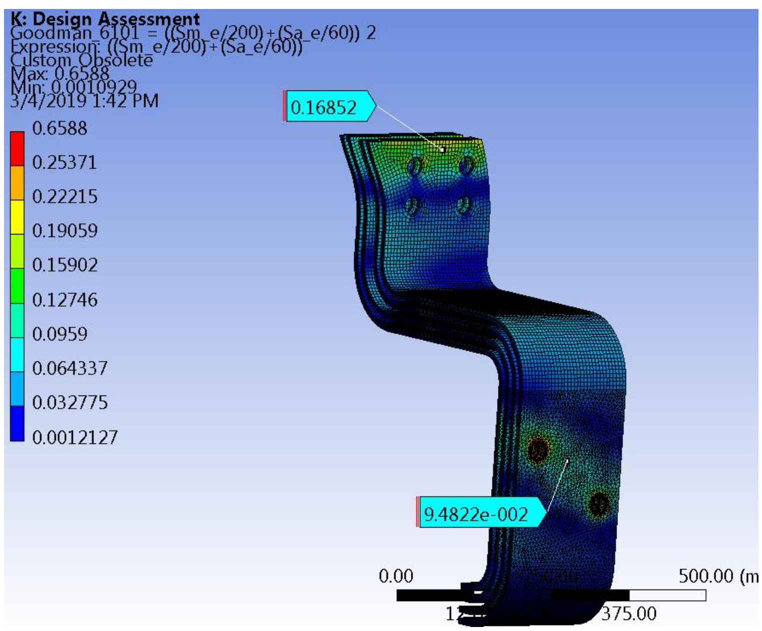


Fig 16 the Goodman equation (1/SF) plot for the Al 6101-T6.

$$\frac{\sigma(alt)}{Sf} + \frac{\sigma(mean)}{Su} = \frac{1}{SF}$$

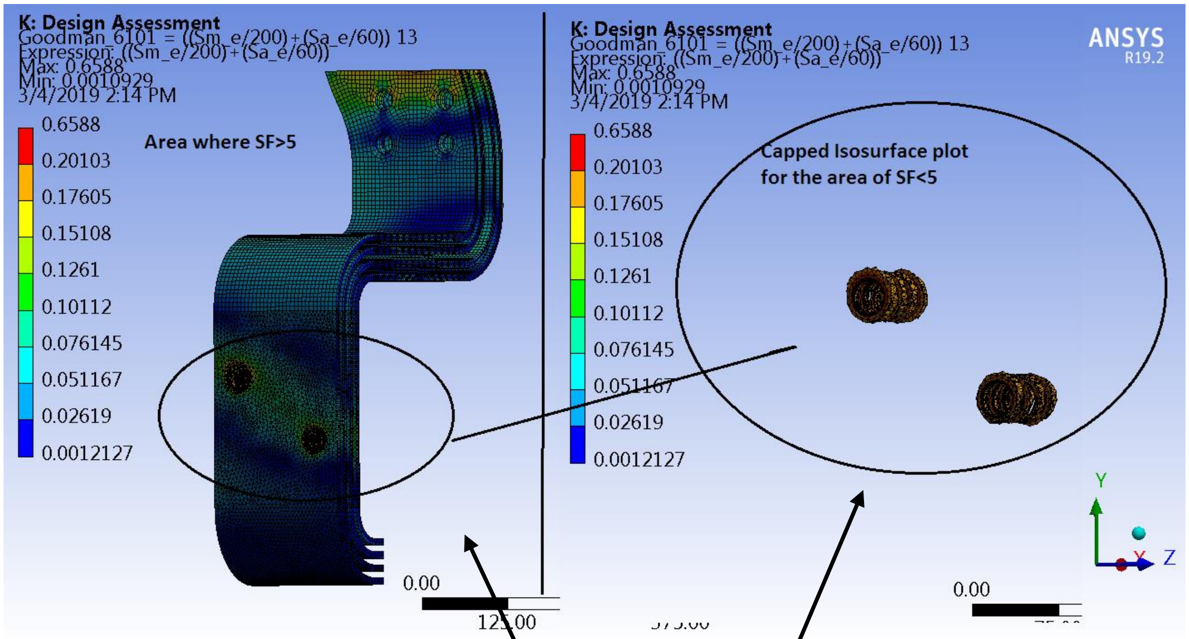


Fig 17 The area (Al6101-T6) with SF>5 vs SF<5 area

SF of is very high for the stripline with an exception of around bolt hole area which is very small portion of the structure. Further study with a sub model in that area indicates as shown in Fig 18 through Fig 25.

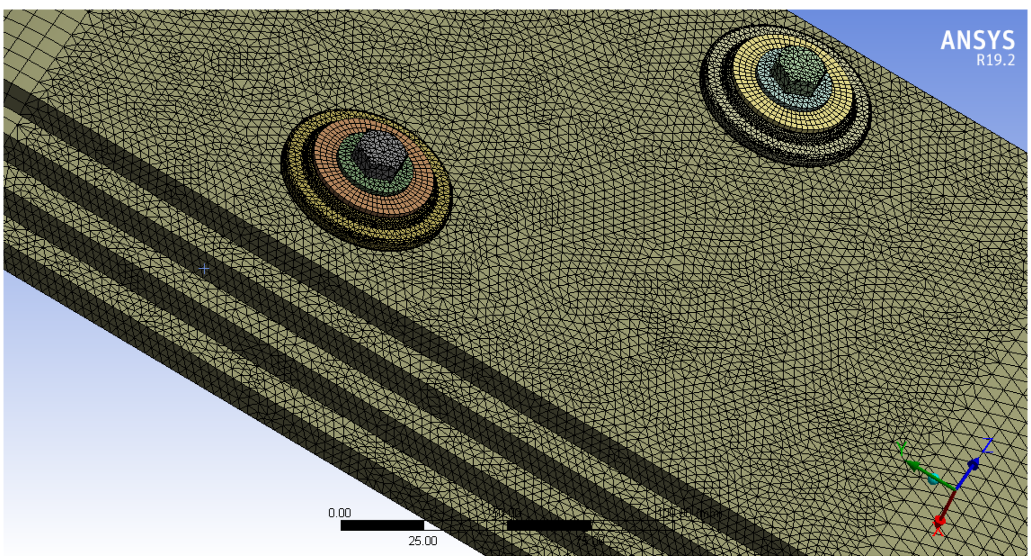


Fig 18 a sub-model approach used around the bolt area with a refined mesh

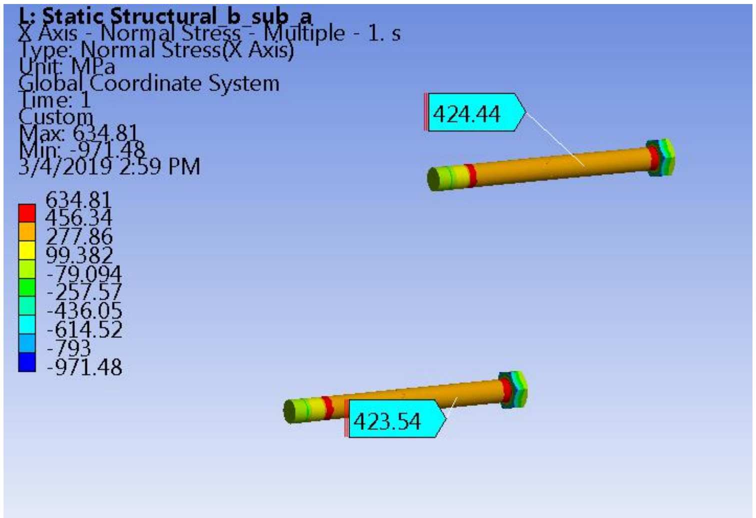


Fig 19 the bolt stress of preloaded 6800 lbf_ sub model

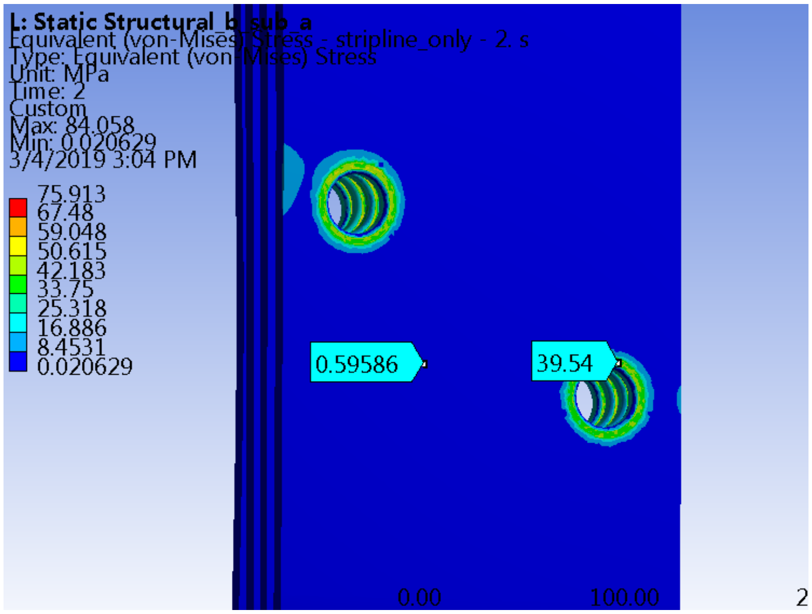


Fig 20 thermal stress _ sub model (MPa)

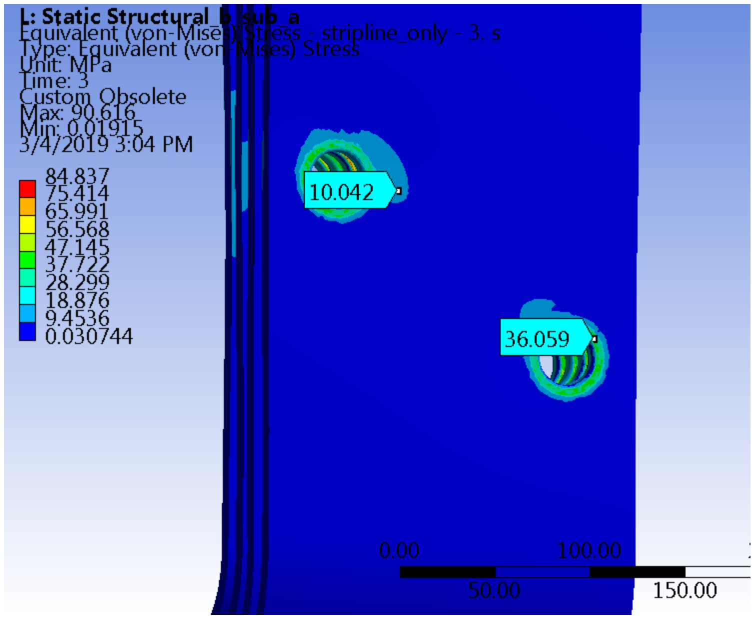


Fig 21 Thermal + magnetic _sub model (MPa)

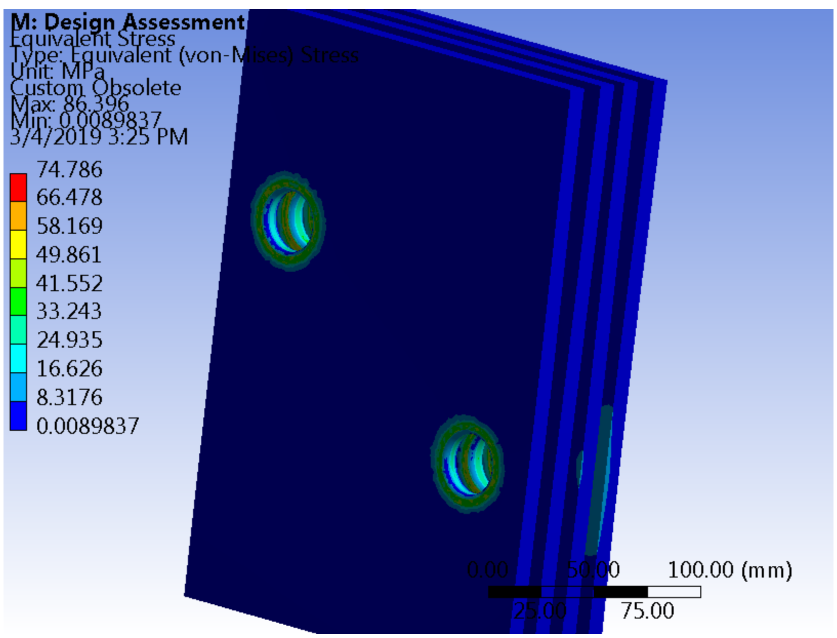


Fig 22 the mean stress Sm MPa

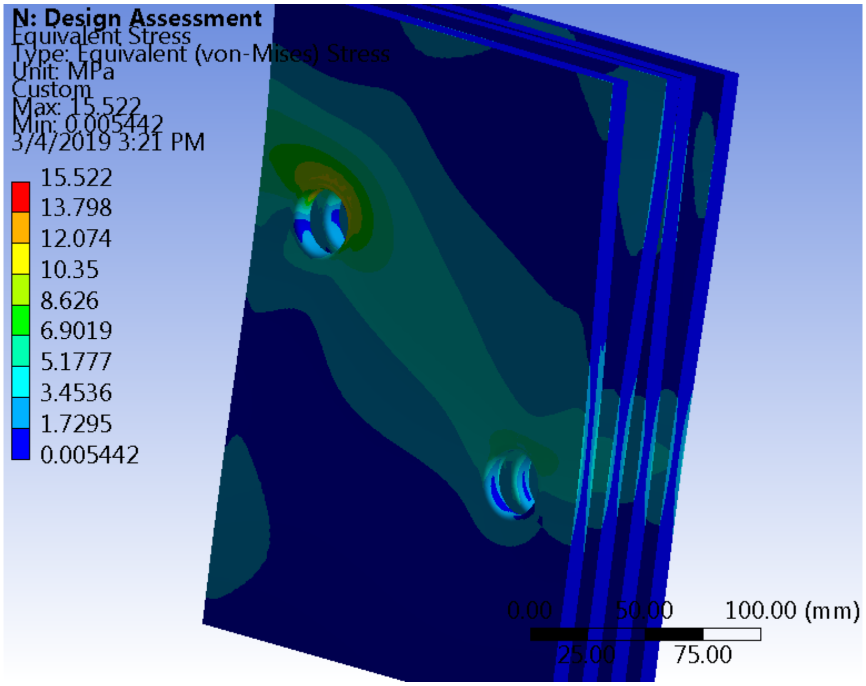


Fig 23 alternating stress Sa MPa

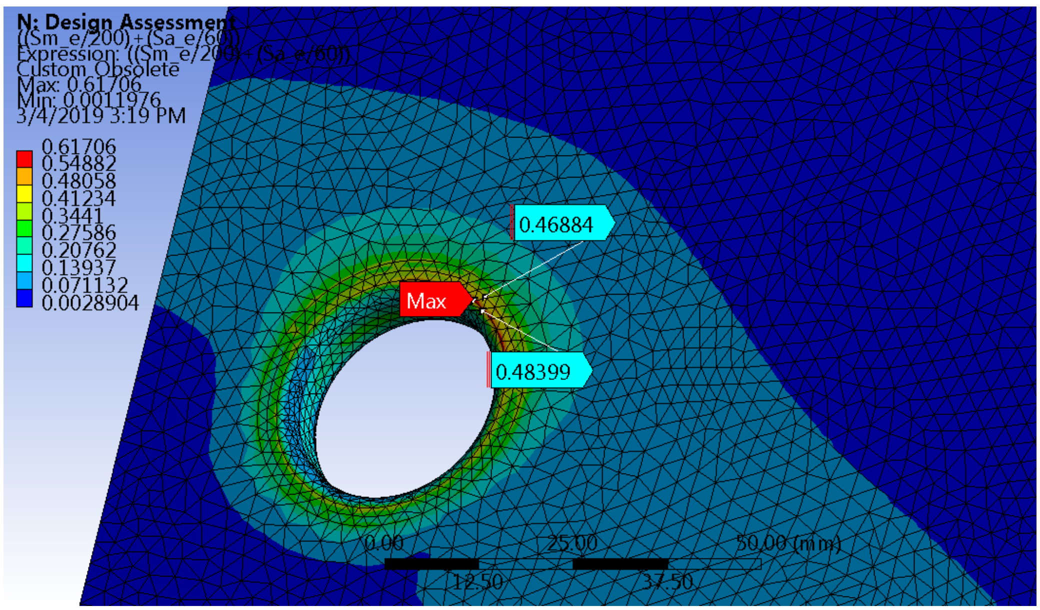
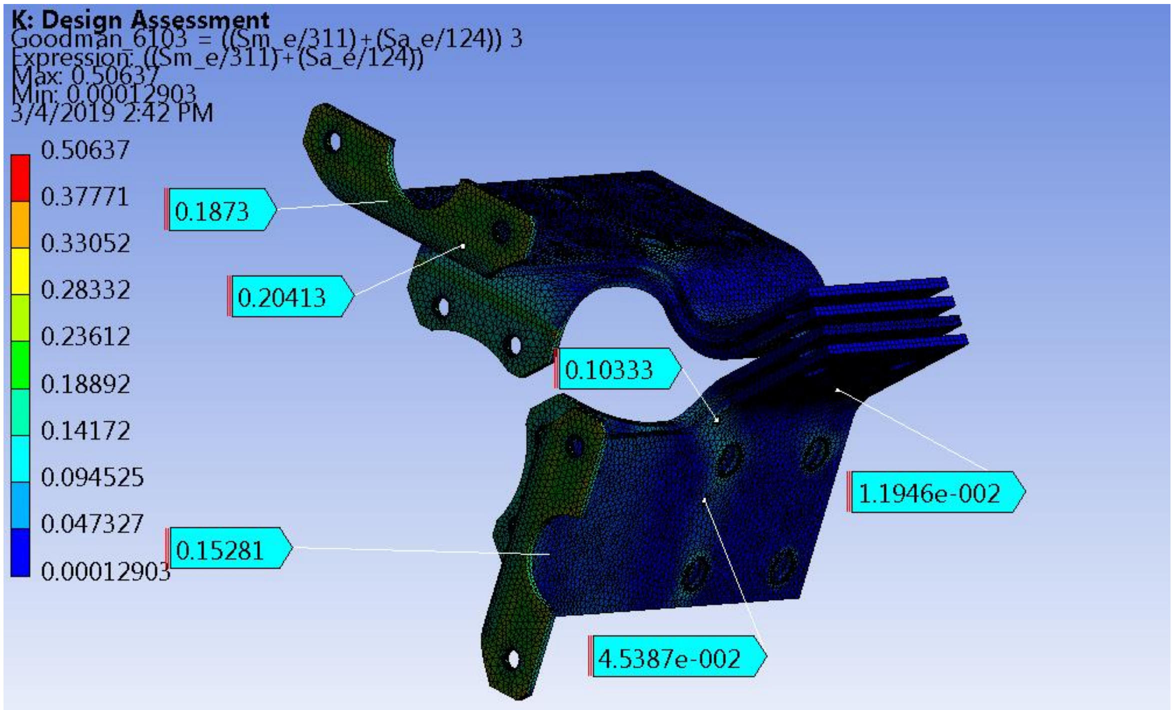


Fig 24 the Goodman equation plot (1/SF)

Note: SF= 1/0.61=1.64 (based on the tiny area of peak number). If one moves just slightly away, SF will be 1/0.48=2.08.

Al 6013 area



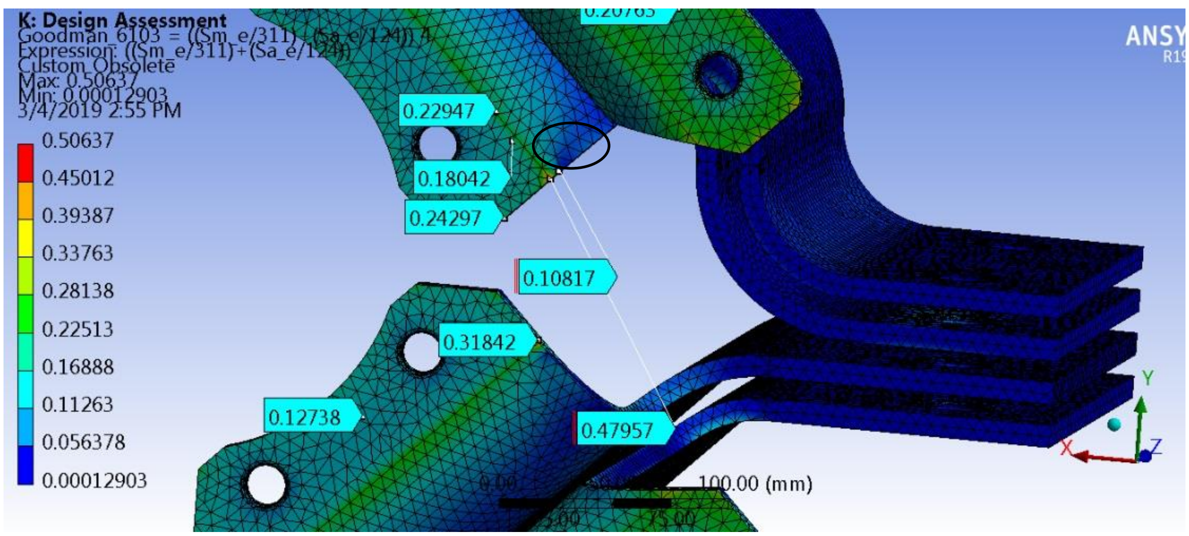


Fig 25 Goodman equation (1/SF) for section of Al 6013-T6.
SF should be >2 at least, or much high if it is away from the tiny area

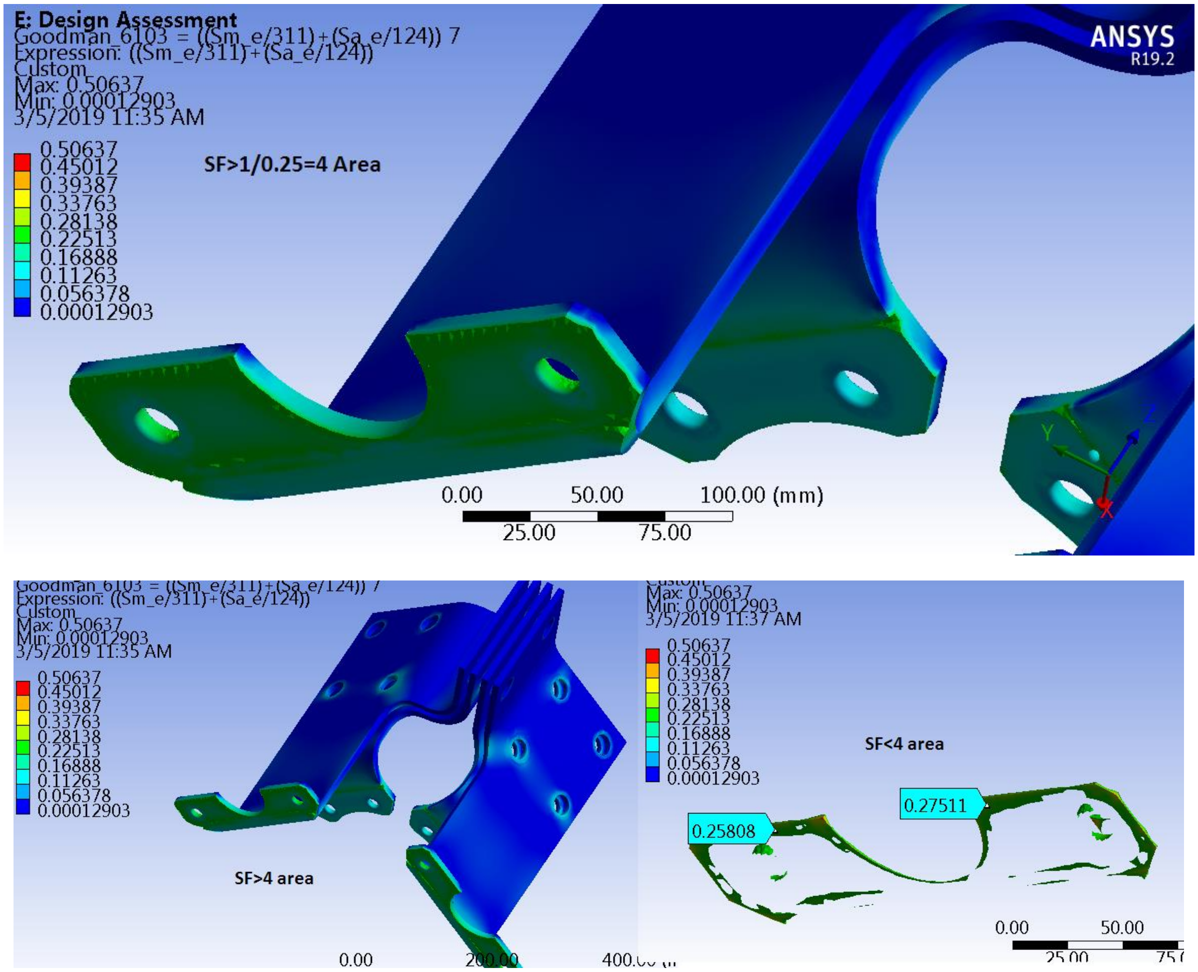


Fig 26 SF>4 area vs SF < 4 area

Note: SF > 4 is in the majority area with an exception of the peak value at the fixed boundary, which still has SF=1/0.5=2. Slightly away from that point, SF will be much high >4 (1/0.108>4)

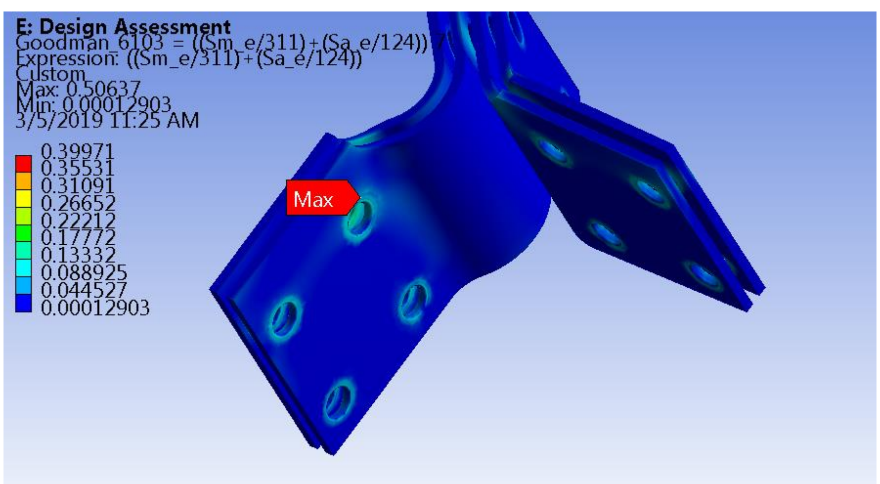


Fig 27 1/SF for the bolt hole area (Al6013-T6)

Conclusion

With the latest measured convective film coefficient, the stripline temperature is getting much improved. The maximum temperature is <100.2 C. The fatigue SF is also high for the stripline as summarize in Table 2.

Table 2 Summery of Safety Factor

SF (min)	Stripline (away from bolt hole)	Bolt hole	Connection area with horn
Al 6101-T6	SF>5	SF=1.64 (based on the peak number)	N/A
Al6013-T6	SF>4	SF=2.5 (based on the peak number)	SF=2 (based on the peak number)

Reference

1) Zhijing Tang, “Finite Element Analysis of Strip lines of Horn 1”, March 9, 2018

Appendix A

Measured film coefficient (Provided by Cory Crowely and Georgi Lolov

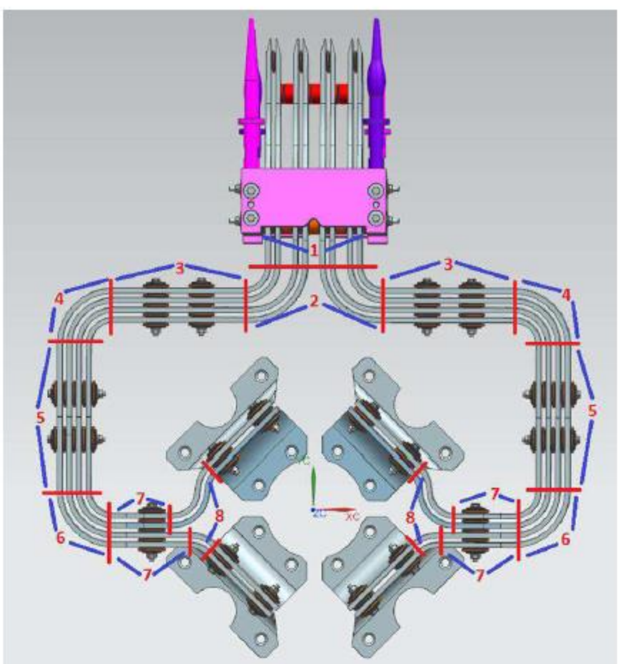
Hi Ang,

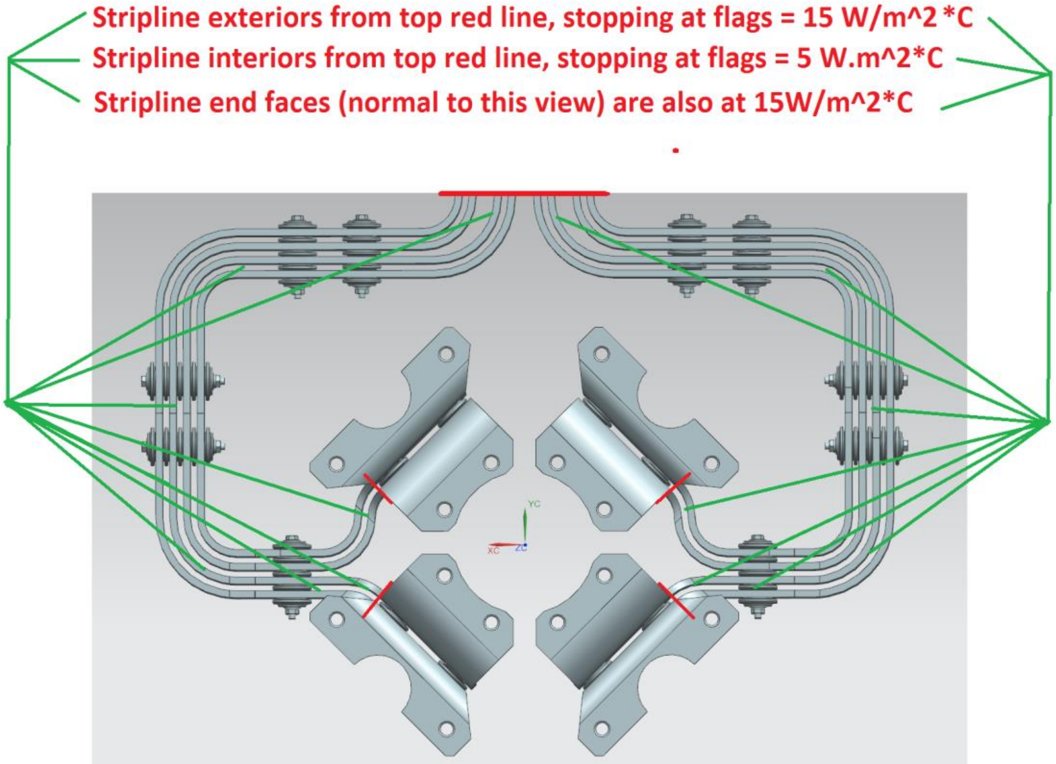
We've finished testing the outer layers in the wind tunnel with the new diverters and have actually achieved some great results. Even with some significant de-rating, we feel that the following regions can be updated based on the picture below:

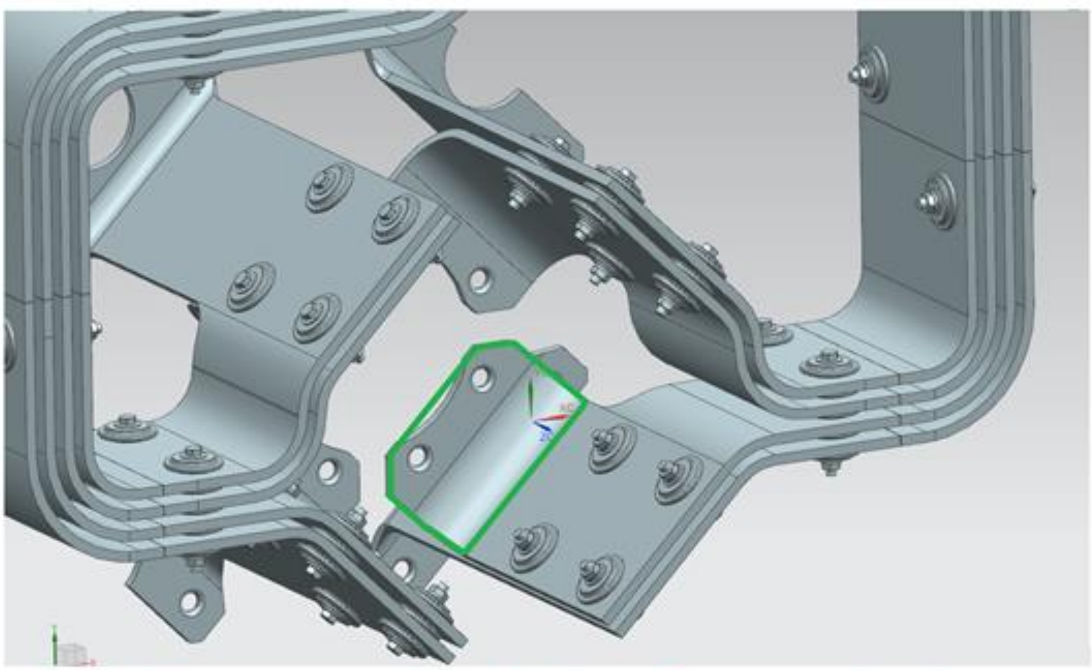
1. Regions 6, 7, & 8 exterior surfaces: h=75 W/m^2*C
2. Regions 6, 7, & 8 interior surfaces: h=40 W/m^2*C
3. Region 5 exterior surface: h=25 W/m^2*C
4. Region 5 interior surface; h=15 W/m^2*C

Would you be willing to update the steady state analysis with the new data? If the temperatures look acceptable, we would then like to move forward with the revised transient / structural analysis pending your availability. Let me know what you think; I know you guys are fairly busy.

Regards,
Cory

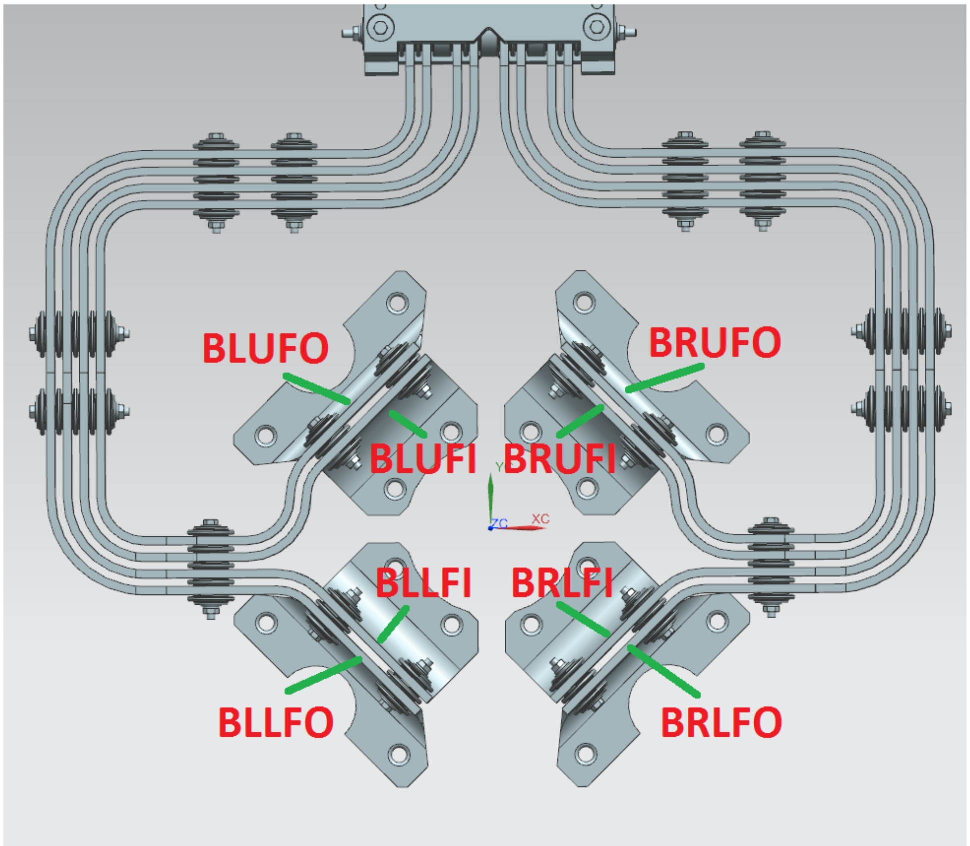






All exterior radii and tab surfaces outlined in green are to be increased to 15W/m^2*C.

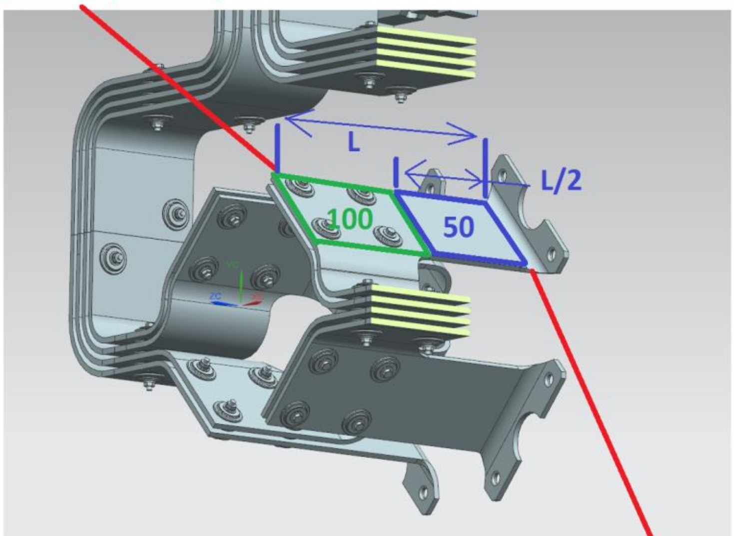
Beam direction is out of screen towards viewer. View is looking at stripline as viewed from downstream end of horn 1.



See table for flag convection coefficients corresponding to labels shown.

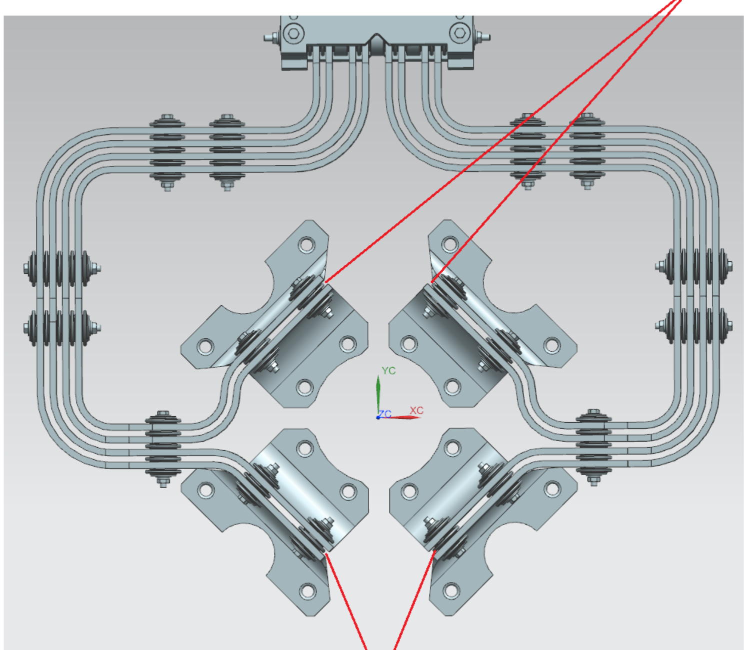
Location	Convection Coefficient (W/m^2*C)
BLUFO & BRUFO	100
BLUFI & BRUFI	50
BLLFI & BRLFI	65
BLLFO & BRLFO	50

This area (green) supports
full cooling (~100 W/m^2*C)

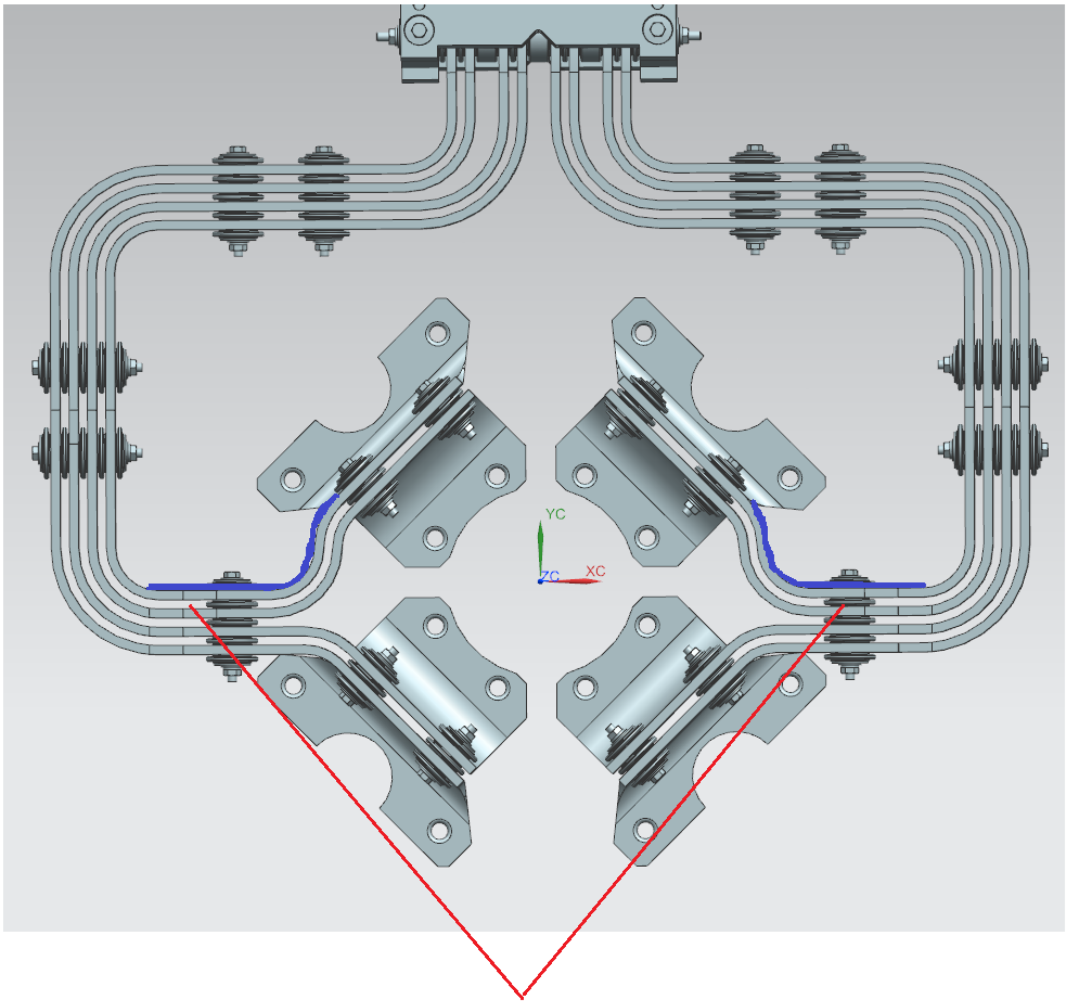


1/2 the depth of the exterior flag surface should support
1/2 the obtained convection coefficient exhibited in the
green section. (1/2 * 100 = 50 W/m^2*C)

Inside layers of upper flags
should assume 5 W/m^2*C



Inside layers of lower flags
should assume 10 W/m^2*C



Exterior layers highlighted in blue can assume a convection coefficient of 50 W/m^2*C

Appendix B

The Material Properties used in the Analysis (From reference 1)

Table I. Material Properties used in the Analysis

	Aluminum 6101_T6	Ceramics Zirconia	Titanium 6Al-4V
ρ (kg/m^3)	2700	3920	4430
E (GPa)	69	370	114
ν	0.33	0.22	0.34
α (μm/m-C)	23.4	8.2	8.6
k (W/m-C)	200	2.2	6.7
C (J/kg-C)	896	880	526
σ (Ω-m)	-	1e12	178e-8

	Resistivity (Ohm-cm)	
Temp (C)	6101-T61	6013-T6
25	3.0426E-06	3.9980E-06
40	3.2373E-06	4.2367E-06
60	3.4907E-06	4.4918E-06
80	3.7370E-06	4.7243E-06
100	3.9825E-06	4.9639E-06

Table V. Material strength used to calculate safety factors

Alloy/Temper	Ultimate stress (MPa)	Yield stress (MPa)	No of cycles	Fatigue Stress (MPa)
6101-T6	200	172	10^7	90
			10^8	60
6013-T6	311	286	10^7	172
			10^8	124

Material strength data

Typical Mechanical Properties of Aluminum 6101						
Temper	**Tensile**					**Hardness**
	Ultimate		**Yield**		**Elongation**	**Brinell**
	KSI	MPA	KSI	MPA	%	
T6	29	200	25	172	15	71

From *Properties of Aluminum Alloys: Fatigue Data and Effect of Temperature*, we have fatigue strength of 90 MPa for 10 million cycles and 60 MPa for 100 million cycles for R = -1.

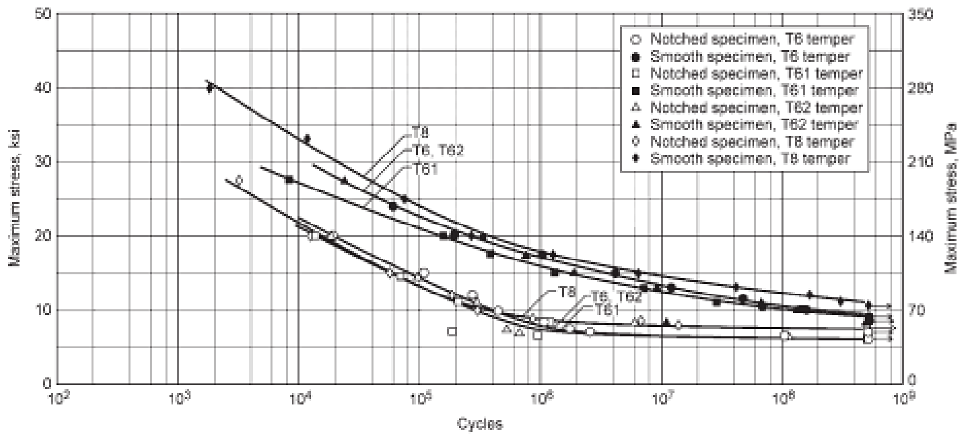
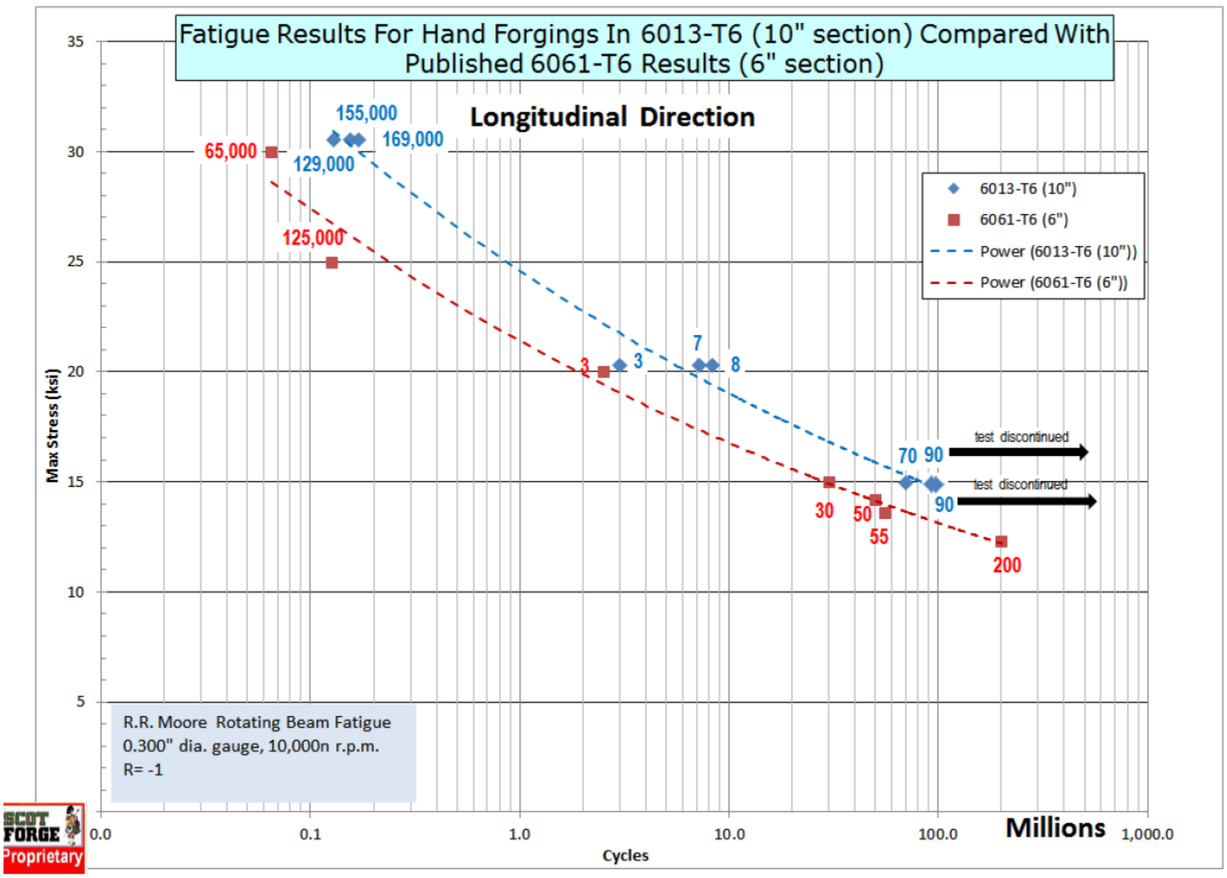


Fig. 6101.RB01 Rotating-beam ($R = -1.0$) fatigue curves for 3/4 in. diam 6101-T6, T61, T62, and T8 rolled and drawn rod, smooth and sharply notched specimens

FATIGUE PROPERTIES - Improved fatigue is realized for 6013 –T6 as compared to 6061-T6.



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